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Fume and gas emission during arc welding: Hazards and recommendation

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ABSTRACT

Welding is the principal industrial process used for joining metals, but at the same time, it's the significant source of toxic fumes and gases emission. With the advent of new types of welding procedures and consumables, the number of welders exposed to welding fumes is growing constantly in spite of the mechanisation and automation of the process. Having in mind that, in some cases, toxic fumes and gases can be over the respective limits for toxic substances, one of the most important requirements for chosen welding procedure is its harmlessness to the environment. The health aspects associated with welding are complex and the industry is continuing its research to evaluate the effects of the welder's exposure to typical constituents of welding fumes and gases, as well as its impact on what concerns climatic changes. The aim of this paper is to estimate the influence of the type of filler material on the emission of toxic substances, and to show the potential hazards. In order to determine that effect, microalloyed steel has been welded using two different filler materials (metal cored wire and self-shielded wire). The concentrations of emitted total dust, CO_2, CO, SO, Mn, Ni, Al, Cr, Cr(VI), Ca and P were measured. By comparing results for both filler materials, it was established that the special attention must be paid to the high concentration of manganese and CO in metal cored wire, as well as high concentrations of phosphorus and aluminum in self-shielded wire. Also, conducted experimental measurements of emission of certain elements did not show higher toxicity of self-shielded wire compare to metal cored wire, what is in the contrast with previous studies.

Contents

1. Introduction

Welding is the principal industrial process used for joining metals. It's a particular technology in the sense that it is needed in almost all kinds of metallic constructions [1]. In this sector; there are about 730 000 full time and 5.5 million welding related jobs in

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Europe. Worldwide, industry lays down an estimated one million tons of weld metal annually. Based on an average fume production of 0.5% of weld metal, an estimated five thousand tons of fume are produced annually. With the advent of new types of welding procedures and consumables, the number of welders exposed to welding fumes is growing constantly in spite of the mechanisation and automation of the process. Presently, some 3 million persons from different professional backgrounds are directly subjected to welding fume and gas action. Most welding processes, by their operation mode and the technological equipment used, have a major impact on the environment and pollution is not in the least negligible [2]. Various fumes and gases can be generated during welding. Welding fumes are metal-containing aerosols consisting of particles formed through complex vaporisation–condensation–oxidation processes during welding. Welding fume gets into the welder's body mainly through the breathing organs, because welding fume particles are among the most respirable ones. The health effects associated with metal fumes depend on the specific metals present in the fumes, but there is a concern that these may range from short-term illnesses, such as metal fume fever, to long-term lung damage and neurological disorders, such as lung cancer and Parkinson's disease. Gas phase pollutants are also generated during welding operations; known gaseous pollutants include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ozone (O_3).

The main goal in every advancement of welding processes throughout the years was first, to improve the integrity of the weld, and second, to improve upon the process-to make it faster, more efficient, and more cost effective through higher productivity [3]. Finally, in nowdays, one of the most important requirements is the health aspects associated with welding and cutting and the industry is continuing its research to evaluate the effects of the welder's exposure to typical constituents of welding fumes and gases and its impact on what concerns climatic changes.

The reasons for estimating emissions dictate the level of effort required, the data quality objectives and the resources required. The most important step in the emission estimation process is to define the end use and identify potential users of the data. For example emission estimation required to demonstrate compliance with regulatory standards may require more accurate and costly methods than those intended for the purpose of national inventory reporting [4]. New environmental, health and safety legislation, both in the EU and in the USA, is driving the need for the study of new welding processes, and the selection of the operational procedures that will reduce fume emissions and will promote a healthier, safer and more productive work environment [5]. While the developed countries have set that goal, a great number of developing countries, including Serbia, are still striving to identify such procedures and provide the fundamental preconditions for their more intensive utilization in the future.

2. Welding fumes and gas emission and potential hazards

Welding fumes are very small particles that are formed when the vaporized metal rapidly condenses in air and are typically too small to be seen by the naked eye, but collectively, form a visible plume. Welding fumes consist of metal oxide particles and gases that are formed during welding and they are easily inhaled. The chemical composition of the particles and the amount of fumes produced during welding depend on the welding procedures, the chemical composition of the shielding gases, the filler and the base material, the presence of coatings and the time and severity of the exposure [6].

The primary source of information when determining the components likely to be in the fume is the material safety data sheet of the consumable welding electrode/wire. About 90–95 percent of the fumes are generated from the filler metal and flux coating/core of consumable electrodes. Since the base metal weld pool is much cooler than the electrode tip, the base metal contributes only a minor amount of the total fumes. The only case when the base metal may be a significant factor of the fume exposure if the metal or surface residue contains a highly toxic substance (lead, cadmium, etc.). In addition to the welding technique, studies have shown that the fume generation rate is also influenced by the following factors: electrical current, arc voltage, wire diameter, shielding gas, welding speed and steady/current pulsed current welding [7,8].

Welding fume can be present in different morphologies [9]. Individual spherical particles less than 20 nm are formed by vapor condensation, while aggregates of 20 nm particles are formed by the collision of primary particles. Welding fume particle size can be divided into three groups: ultrafine ($0.01 < d < 0.1$ μm), fine ($0.1 < d < 2.5$ μm), and coarse ($d > 2.5$ μm) [10]. There are several mechanisms by which welding fume can originate. Fig. 1 shows the various methods of fume formation.

When heating of the liquid metal occurs rapidly, metal alloy droplet expulsion occurs and the result is small droplets being forced off of the parent metal droplet. When this metal droplet cools and solidifies outside the presence of oxygen, as in an inert argon or helium atmosphere, mostly metallic particles with a slight oxide layer will occur (Fig. 1a). In cases where inert gas shielding is not used, such as with SMAW (Shielded Metal Arc Welding) or FCAW-S (Self-shielded Flux Cored Arc Welding), the liquid droplet is in direct contact with oxygen and will readily oxidize, Fig. 1b. For inert processes, such as GMAW (Gas Metal Arc Welding) or GTAW (Gas Tungsten Arc Welding), oxygen may be incorporated from the surrounding atmosphere or may be an inherent component in the gas mixture, as in Ar–O_2 mixtures or even Ar–CO_2 mixtures. If heating of the liquid metal is sufficient, vaporization of the metal will occur. Inert atmospheres facilitate fume formation through vaporization and condensation of elemental material with some light oxidation. Fume formed from FCAW and SMAW results from vaporization, condensation, and subsequent oxidation of elemental and lower oxide species, and the vaporization/condensation of oxide and fluoride flux species and compounds, Fig. 1c and d. The chemical composition of fume is, therefore, highly dependent on flux composition since a significant amount of low melting point components are contained within the flux and wind up in the fume particles themselves [9].

The combination of the molten metal with the compounds in the flux or electrode coating can cause chemical reactions that can change the composition of the fume particles. Fume particle morphology and composition are therefore a product of the electrode composition and shielding atmosphere. The characterization of welding fume depends on what the investigator hopes to determine. The materials typically found in welding fume include aluminum, beryllium, cadmium oxides, chromium, copper, fluorides, iron oxide, lead, manganese, molybdenum, nickel, vanadium, and zinc oxides. Each of these elements has harmful effect to human health, but will continue to be listed just some of them.

Manganese: Inhalation of fumes with high concentrations of manganese and its oxides may bring "metal fume fever". Symptoms of metal fume fever are chills and fever, dryness of the throat, weakness and aching of the head and body. Symptoms often occur several hours after exposure to fumes and usually last for only a day. Prolonged or repeated exposure to manganese has long been associated with central nervous system effects which are similar in nature to Parkinsonism. Manganese can cause a degeneration of CNS function that gets progressively worse after symptoms first appear [12].

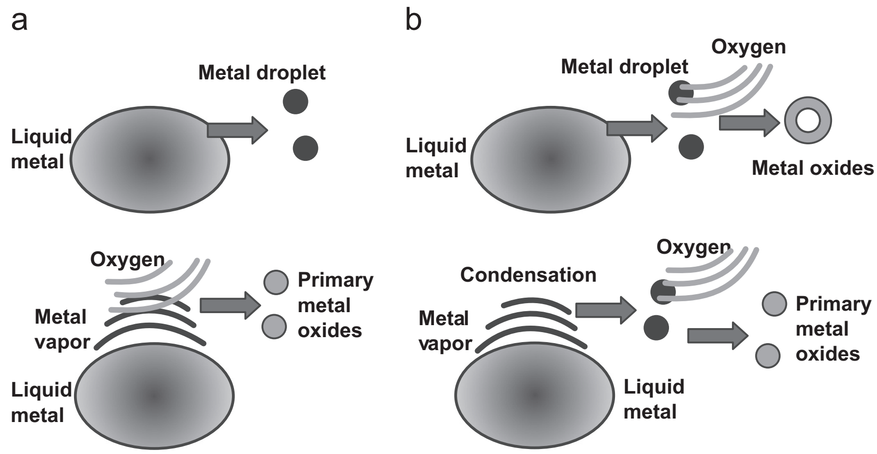

Fig. 1. Fume formation mechanism: (a) metal alloy droplet expulsion; (b) metal alloy droplet expulsion and oxidation; (c) metal alloy evaporation/oxidation; (d) metal alloy evaporation/condensation/oxidation [11].

Chromium: Chromium is an element present in the consumables and base material of stainless steels, heat-resisting steels, some creep-resisting steels, some high nickel alloys, and armour plate. It may also be present in some consumables used for hardfacing. When arc welding takes place on materials containing chromium, or by using consumables containing chromium, some of the chromium will be volatilised and escape from the protective gases in and around the arc. This metal vapour will be oxidised by the atmosphere to give particulate fume. Chromium can be present in fume in different forms: chromium in metallic form (valence state 0), trivalent form (Cr III) and hexavalent form (Cr VI). Trivalent chromium occurs widely in nature and is an essentials nutrient required by the human body to promote the action of insulin in body tissues. Chromium as a pure metal has no reported human or environmental toxity effects. Both acute and chronic toxicity of chromium are mainly caused by hexavalent chromium compounds (Cr VI). Hexavalent chromium is considered the most hazardous of all forms, and in welding fume it is a suspected human carcinogen. DNA damage in welders has been associated with hexavalent chromium exposure [13]. This is consistent with the classification of hexavalent chromium as a human lung carcinogen [14]. Unfortunately, chromium welding exposures can be difficult to control.

Nickel: Metallic nickel and certain soluble nickel compounds as dust or fume cause sensitization dermatitis and probably produce cancer of the paranasal sinuses and the lung; nickel fume in high concentrations is a respiratory irritant [15].

Aluminium: Chronic aluminium exposure is associated with Alzheimer's disease; recent review identified how aluminium may contribute to the formation of Amyloid proteins in the brain, a marker of Alzheimer's disease [16].

Phosphorus: Phosphorus spontaneously burns in air, and the vapors released are irritating to the respiratory tract and eyes. The early signs of systematic intoxication by phosphorus are abdominal pain, jaundice, and a garlic odor of the breath; prolonged intake may cause anemia, cachexia and necrosis of bone [17].

Gases are also generated from welding, which may include carbon monoxide, carbon dioxide, sulphur dioxide, ozone and nitrogen oxides.

Carbon monoxide (*CO*) is an odorless, colorless and tasteless gas and cannot be detected by the senses [18]. It may be formed by the incomplete combustion of the electrode covering or flux and by the use of carbon dioxide (CO_2). Overexposure to CO inhibits the body's red blood cells to sufficiently carry oxygen to other tissues within the body, which subsequently results in asphyxiation. Symptoms of overexposure include pounding of the heart, a dull headache, flashes before the eyes, dizziness, ringing in the ears and death. High concentrations may be rapidly fatal without producing significant warning symptoms. The effects are also more severe in people who are working hard and in people who are working in places where the temperature is high. Welding does not normally generate CO at high enough levels to be a concern; however, high levels of carbon monoxide may potentially accumulate when welding or air arc gouging in confined spaces. There is also a potential of an oxygen-deficient atmosphere if welding inside of a confined or enclosed space if an inert gas (such as argon) is used as the shielding gas.

Carbon dioxide (CO_2) is primarily a colorless, odorless gas. In the earth's atmosphere, it acts as a "greenhouse gas" which plays a major role in global warming and anthropogenic climate change. Human activities are altering the carbon cycle and have contributed substantially to climate change by adding CO_2 and other heat-trapping gases to the atmosphere. With a global radiative forcing of 1.74 W/m^2, CO_2 is the largest contributor among well-mixed long-lived greenhouse gases, accounting for more than 63% of the total [19]. For the first time in history, the share of CO_2 emissions from developing countries was in 2008, 50.3%; just larger than those of industrialized countries (46.6%), which have an emission mitigation target under the Kyoto Protocol, and from international transport (3.2%) together. Fossil fuel combustion accounts for about 90% of total global CO_2 emissions in 2011, excluding those from forest fires and the use of wood fuel [20].

Fossil fuels dominate in the global energy production market contributing 80% of the primary energy demands. Fossil energy use increased most in 2000–2008, mostly due to the improvement in the quality of life [21]. Further, half of the increased energy use is coal, growing faster than all renewable energy. Since Chernobyl disaster in 1986, investments in nuclear power have been small. The volume of renewable energy is not yet substituting fossil energy use [22].

Furthermore, a large number of researches have shown that CO_2 emissions within a country are closely related to its economic growth, industrialization, urbanization, population structure, and technology level [23].

Beside its influence on climate changes, CO_2 can be dangerous to human health. Inhaling carbon dioxide during welding may cause rapid breathing, rapid beating of the heart, headache, sweating, mental depression and death.

Sulfur dioxide (SO_2) is one of a group of highly reactive gasses. It is a toxic gas with a pungent, irritating smell, that is released in various industrial processes, such as welding. Sulphur oxides (SO_x) is, together with nitrogen oxides (NO_x), major combustion-generated

pollutants from coal-fired power plants. Oxides of sulphur are a major contributor to acid rain [4]. According to EPA (United States Environmental Protection Agency), the largest sources of SO_2 emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment. According to the European Environment Agency, emissions of sulphur dioxide (SO_2) have decreased by 76% between 1990 and 2009. In 2009, the most significant sectoral source of SO_x emissions was Energy production and distribution (70%), followed by emissions occurring from Energy use in industry (13%), in the Commercial, institutional and households (9%) and in the Industrial processes sector. In Serbia, primary emissions of SO_2 come from fossil fuels combustion processes, especially from thermal power plants. In every thermal plant in Serbia, emission values of SO_2, NO_x and powdery substances exceed limit values and it is expected that the first demands by European Union in this subject area will be directed to the facilities of Electric Power Industry of Serbia for reducing sulphur oxides emissions [24]. SO_2 is linked with a number of adverse effects on the respiratory system. Currently, sulfur dioxide and five other major pollutants are listed as criteria pollutants. The others are ozone, lead, carbon monoxide, nitrogen oxides, and particulate matter. Sulphur dioxide is emitted when fuels containing sulphur are combusted. It is a pollutant which contributes to acid deposition which in turn can lead to potential changes occurring in soil and water quality. The subsequent impacts of acid deposition can be significant, including adverse effects on aquatic ecosystems in rivers and lakes and damage to forests, crops and other vegetation. SO_x emissions also contribute as a secondary particulate pollutant to formation of particulate matter in the atmosphere, an important air pollutant in terms of its adverse impact on human health. Current scientific evidence links short-term exposures to SO_2, ranging from 5 min to 24 h, with an array of adverse respiratory effects including bronchoconstriction and increased asthma symptoms.

Ozone, *nitrogen dioxide and nitric oxide* are produced by the interaction of ultraviolet light (from the welding arc) with the surrounding air. These compounds are irritating to the eyes, nose and throat. High exposures can also cause shortness of breath, chest pain, fluid in the lungs and other long term pulmonary illnesses.

Workers can be exposed by inhaling, ingesting, and coming into skin contact with the fume. All three can be important contributors to disease outcome. Inhalation is the primary, but not only, route of exposure. Workers can also be exposed to welding-related metals through ingestion and skin contact. This needs to be taken into account when evaluating worker exposure as welders eating with dirty hands or eating or drinking contaminated food/liquids can ingest a significant dose [9]. This route is important because lung cancer has been associated with human consumption of drinking water containing high levels of arsenic and chromium. Additionally, a number of metals (including beryllium, chromium and cobalt), can directly affect the skin (irritation and allergic impacts) or be absorbed through the skin and cause lung damage and other health effects. Skin absorption is enhanced by small particle size and by cuts or other damage to the skin.

3. Welding processes

The type of welding process is directly related to the amount of fumes and gases that are generated. Therefore, it is important to have a basic understanding of the welding process in order to assess the risk of exposure.

Gas metal arc welding (GMAW) has been known since the 40-ies of past century. The wire feed processes of gas metal arc and flux core welding consume over 70 percent of total filler materials used today and this percentage continues to grow. The filler material for this process can be in form of solid wire, flux cored wire and self shielded wire. Around 1957, the flux cored arc welding process as it known today was introduced to the market [3]. Flux core arc welding (FCAW) is used for carbon steels, low alloy steels and stainless steels. This welding process has similarities to both SMAW (Shielded metal arc welding) and GMAW. The electrode wire has a central core containing fluxing agents and additional shielding gas may be supplied externally. The powdered flux provides alloying elements, arc stabilizers, denitrides, deoxidizers, slag formers, and shielding gas generating chemicals [25]. Flux cored wires provided improved joint penetration, smooth arc transfers, low spatter levels, and overall, easier to use than solid wires. Flux cored wires in relation to the chemical composition of a core are divided into rutile flux cored, basic flux cored and metal cored wires.

3.1. Metal cored wires

Flux cored wire manufacturers and fabricators still sought improvements in the process. They needed to overcome one last hurdle, to achieve both high deposition efficiencies. The goal was to attain the high productivity level of flux cored wires, but maintain the high deposition efficiencies of the solid gas metal arc welding wire [26]. The fabricated composite wire known as metal cored wire was the result. The main constituents of inner core are silicon, manganese, aluminium, titanium and zirconium (alloying, deoxidising and nitrogen-fixing elements) as well as chromium, nickel, molybdenum and vanadium. These elements are added to a core as metallic powders, metallic oxides, or ferroalloys. Besides, in cores we can also find such alkaline metals as calcium, sodium, potassium and barium; all of them in chemical compounds-mainly carbonates or silicates [27]. To produce the new generation of cored wires, manufacturers are utilizing proprietary technology to alter the composition of both the metal strip and the components used to fill the core. Whereas their construction resembles flux cored wires, metal cored wires are much closer to solid wires in matters of performance and usability. One of the most significant improvements in the new generation of metal cored wires is the reduced fume level exhibited over a range of welding parameters. Since this new generation of metal cored wires produces fume levels from 20 to 50% lower than comparable flux cored wires, they can be used in applications where fumes must be reduced.

3.2. Self-shielded wire

Basic difference between flux-cored and self shielded (FCAW-S) wires is that the first requires an external shielding gas, and the second does not. FCAW-S wires require very simple welding guns, are ideal for outdoor use because they tolerate wind/weather, and although they typically generate a greater amount of fume per welded joint, the welding zone can be kept safe by extracting the fumes. During self-shielded flux cored wire welding, arc and weld pool shielding is provided by gases and fumes of metals created as a result of disintegration of flux core constituents as well as by slag-forming constituents of the core. The disadvantages related to these wires consist in the emission of weld fumes containing, among others, very harmful barium compounds. The possibility of welding without additional gas shielding depends on a proper amount of deoxidising and nitrogen-fixing constituents, first of all, aluminium, titanium, zirconium, and alloy components such as manganese, nickel and silicon. Arc and pool shielding during the

Table 1
Chemical composition of base material.

Chem. element	C	Si	Mn	P	S	Al	Ni	Cr	V	Nb	Ti
(wt%)	0.15	0.38	1.4	0.015	0.0021	0.031	0.63	0.037	0.099	0.038	0.004

Table 2
Chemical composition of filler material.

Chem.element (wt%)	C	Si	Mn	P	S	Al
Metal cored wire	0.05	0.55	1.4	–	–	–
Self-shielded wire	0.17	0.1	0.5	0.010	0.003	0.5

welding process is created by low-melting, easily evaporating and boiling in the arc iodides, bromides, chlorides and fluorides of alkaline-earth metals and alkali metals. The FCAW-S wires are unique not because they are applied "open arc" but because the air enters the arc and participates in the making of the weld. All the FCAW-S wires must cope with the air during the making of the weld. Air is the source of the nitrogen that is found in the deposit of FCAW-S wires. Diatomic nitrogen is the main constituent of air and is normally thought of as a relatively inert gas; oxygen, the other major diatomic constituent of air, is recognized as a reactive gas. Iron and steel have a propensity to react with and to dissolve elemental nitrogen. When an arc is applied in air, nitrogen and oxygen are believed to dissociate into elemental constituents and nitrous oxide [28]. These reactive species of nitrogen are believed to saturate the weld pool. Unfortunately, the amount of nitrogen in the liquid weld pool exceeds the solubility limit of the solidified weld metal. If nitrogen exceeds the solubility limit at solidification and conditions are favorable to nucleate bubbles, then the nitrogen must be depleted by a chemical reaction and the product of the reaction must not degrade the weld deposit [29]. The amount of nitrogen that enters the weld pool can be diminished by adding certain elements to the core, by impeding the diffusion into the liquid pool and altering the welding parameters.

The element most often used to combine with the nitrogen dissolved in the liquid weld pool is aluminium. Therefore, the self-shielded weldments generally have a higher aluminium content, so is expected to appear in the welding fume.

4. Materials and experimental procedures

The plates of microalloyed steel with chemical composition given in Table 1, were welded with FCAW process. As the filler material, the metal cored wire Filtub 12 M (ø 1.2 mm) and self-shielded wire ESAB Coreshield 8 (ø 1.6 mm) with chemical compositions given in Table 2, were used.

Filtub 12 M is metal cored wire recommended for welding similar types of steels, including fine-grained steels. Because metal cored wires do not result in a slag covering the weld, they combine the benefits of the high deposition rates found in flux cored wires and the high efficiency rates of solid wires. Features of this wire included good bead appearance with small spatter, no slag and therefore without cleaning between runs, good restricting characteristics and high mechanical properties at low temperatures. Classification (AWS-SFA-5.20: E 71T-1, prEN 758:T 46 4 MM2). As shielded gas for welding with this wire, mixture Ar+5.9% CO_2+1.1%O_2 was used with gas flow rates 12 l/min for root pass and 18 l/min for filler pass.

Coreshield 8 is an all-position self-shielded flux cored wire designed to weld critical demand structural applications while

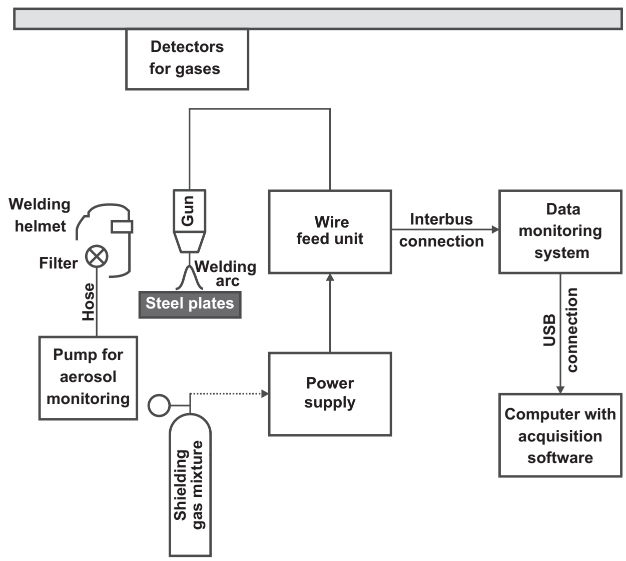

Fig. 2. Scheme of the welding monitoring system.

maintaining excellent arc characteristics and high welder appeal. With its fast-freezing slag that supports the molten metal during welding, Coreshield 8 is ideal for out-of position welding in structural fabrication and other heavy duty applications. Classification (AWS 5.20; E71T-8D). Since the wire is self-shielded, no shielded gas was used.

The plates were welded in five passes: one root pass+four filler passes, with welding current 120 A for root pass and 220 A for filler passes. A conventional power supply Kemppi Fast MIG Pulse 350 and the data monitoring system, which acquires the arc voltage, current intensity and wire feed speed during welding, were used.

The qualitative and quantitative determination of dusts and gases emitted during welding was conducted at the station showed in Fig. 2. The welding process was carried out with the fume extractor switched on.

Welding worker exposures are usually measured in the breathing zone [30]. Since the aim of this experiment was to evaluate actual exposure, the filter or other sampling media should be placed under the welding helmet, Fig. 3.

The emission of gases during welding was measured directly by instrument MSA AUER ORION PLUS. The following gases were measured: carbon monoxide, carbon dioxide and sulfur dioxide. Type of detector for carbon dioxide is an infrared sensor, and type of detector for toxic gases (carbon monoxide and sulfur dioxide) is the electrochemical sensor.

Total welding fume are collected on filters (0.8 μm 0.37 mm MCE-mixed cellulose ester) contained in cassettes, with Casella Apex pump for aerosol monitoring Casella Microdust Pro. The MicroDust Pro instrument uses a modulated beam of infra-red light projected into a measurement chamber. Particles that are tested retracts into the chamber, which is located in the center of the probe. When dust particles enter the sample volume, the beam of infra-red light is scattered within a narrow angle (12–20°) to the receiver. By using a narrow angle of scatter, the instrument is

Fig. 3. Welding helmet with sampling media.

Table 3
Starting environment conditions.

	Initial concentration of gases and dust (mg/m^3)	Max. allowed concentration by standard (mg/m^3)
SO_2	0.77	5
CO	1.6	55
CO_2	910	9000
Total dust	0.937	15

Table 4
Chemical composition of welding fume.

	Concentration of elements in the welding fume (mg/m^3)						
	Mn	P	Al	Ni	Ca	Cr	Cr (VI)
Metal cored wire	16.86	–	1.809	0.1741	0.717	0.0785	0.0272
Self-shielded wire	2.574	2.376	8.564	0.0742	0.4356	0.00495	0.0287

made less sensitive to variations in the refractive index and colour of measured particulate. The amount of scatter is proportional to the mass concentration and is measured by the photo detector. Instrument range is 0–2500 mg/m^3, resolution 0.001 mg/m^3, error ≤ 2.

Total welding fume samples are analyzed for specific contaminants: Cr, hexavalent Cr(VI), Ca, Ni, Al, Mn and P. Analytical method is modified EPA 29 for all elements, except for Cr+6 analytical method is MDHS 61.

Before the start of welding, in the workshop were measured the following conditions, Table 3.

5. Results and discussion

The chemical composition, i.e. measured concentrations of elements in welding fume are presented in Table 4 for metal cored wire and self-shielded wire. The measured values of gases concentrations and total dust for both samples are shown in Table 5.

Since the each individual constituent of welding fume has own exposure limits, in Figs. 4 and 5 are showned obtained results for both wires and permissible exposure limits (threshold limits) defined by standard. National standard SRPS Z.BO.001/91 was used, that is consistent with NIOSH (National Institute for Occupational Safety and Health) recommendations [31].

Table 5
Concentration of gases and total dust during welding.

	Concentration of gases (mg/m^3)			
	SO_2	CO	CO_2	Total dust
Metal cored wire	2.09	181	3590	35.11
Self-shielded wire	2.62	17.2	5760	34.20

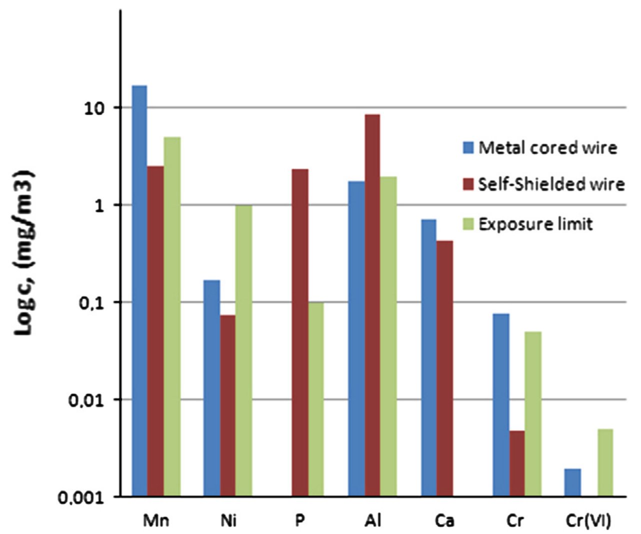

Fig. 4. Chemical composition of welding fume.

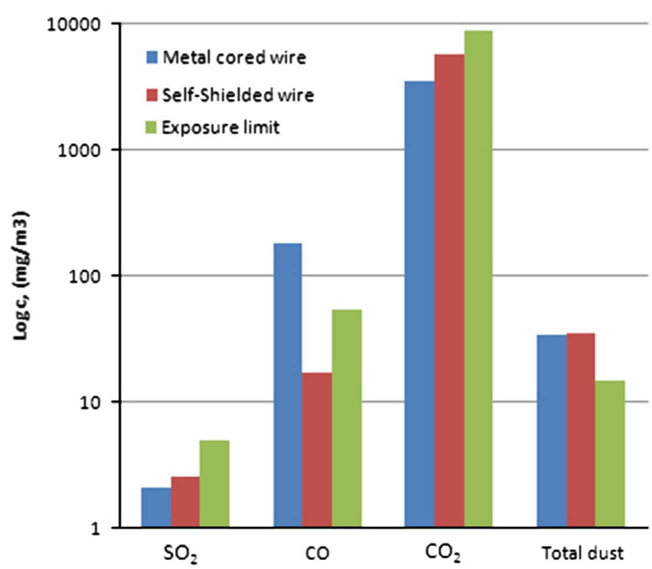

Fig. 5. Emission of gases and dust during welding.

During welding with metal cored wire it can be seen that the concentrations of manganese and chromium are higher than their exposure limits allowed by standard (16.86 mg/m^3 vs. 5 mg/m^3 for Mn and 0.0785 mg/m^3 vs. 0.05 mg/m^3 for Cr). Also, the total dust measured during welding (34.20 mg/m^3) is two times higher than allowable by standard (15 mg/m^3), as the concentration of CO (181 mg/m^3 vs. 55 mg/m^3). The all other concentrations of harmful chemical elements and gases in welding fume are within permissible values.

During welding with self-shielded wire, it can be seen that the phosphorus concentration is considerably above the permissible value (2.376 mg/m^3 vs. 0.1 mg/m^3), as well as aluminium concentration (8.564 mg/m^3 vs. 2 mg/m^3). Also, the total dust measured

during welding (35.20 mg/m^3) is higher than allowable by standard (15 mg/m^3), while the all other concentrations of harmful chemical constituents are within permissible values.

Increased concentrations of Mn in welding fume of metal cored wire is partly consequence of increased content of this element in the flux of these wires that was intentionally added in order to reduce losses caused by oxidation. Also, it is known from literature [8] that Mn fume contents decrease with an increase of CO_2 in the mixture, contrary to the effect of O_2. This behaviour is related to the arc temperature, which decreases with the increase in the CO_2 and with the decrease of the O_2 in the gas mixture. This means that the direct vaporisation of Mn is the mechanism responsible for the presence of those elements in the fumes generated during the metal cored welding. Since the CO_2 content in welding fume of metal cored wire was much lower than in self-shielded fume (3590 mg/m^3 vs. 5760 mg/m^3), it is assumed that this resulted in high manganese concentration.

High levels of carbon monoxide during welding with metal cored wire (181 mg/m^3) may potentially accumulate when welding in confined spaces. There is also a potential of an oxygen-deficient atmosphere if welding inside of a confined or enclosed space if an inert gas (such as argon) is used as the shielding gas. Also, bearing in mind that CO_2 was the component in gas shielded mixture during welding with metal cored wire, and a decomposition of CO_2 to CO and O_2 was occured, while during welding with self-shielded wire this reaction is absent due to lack of gas protection. Anyway, special protection measures must be taken for protection of this toxic gas.

Concentrations of SO_2 and total dust for both wires are approximately the same, which means that they are not a direct consequence of type of filler material.

With the new generation of self-shielded wires, certain elements are adding to reduce Cr(VI) content. For example, according to literature [9], lithium was used to replace potassium in a self-shielded wire. Obviously, the used self-shielded wire belongs to that generation, since the content of Cr(VI) is far below the analytical method level.

Increased aluminium level in welding fume during welding with self-shielded wire is a consequence of increased content of this element in the wire flux. Namely, as already discussed, aluminum in self-shielded wires has a role of deoxidiser and denitrator, which reacts with dissolved oxygen and nitrogen from atmosphere to form oxides and nitrides and to prevent contamination of the weld metal. On the other hand, it is obvious that a large amount of this element is condensed in the welding fume. Having in mind the high toxicity of aluminum, primarily as an element responsible for Alzheimer's disease, it must be taken the special measures for protection when working with these wires.

Finally, special attention must be payed to 20 times higher concentration of phosphorus during welding with self-shielded wire. It is obvious that this element is intentionally added to the flux wire because it burns spontaneously in air and release vapors that protect the weld metal from the surrounding atmosphere.

6. Conclusions

Welding fume as a product of arc welding is an unavoidable chemical and physical emission into environment. Bad influences have to be estimated so that proper measures can be undertaken on protection of welder's health. Welding fume emission, its quantity and composition depend on a various number of factors. In this paper is investigated the influence of welding procedure, i.e. the type of filler material on the fume emission. On the base of the experimental results and their analysis, the following is concluded:

– Metal cored wires and self-shielded wires are relatively new filler materials, and their use hasn't ensured enough experimental data. The new generation of metal cored wires requires special production technology to assure low fume generation rates, while maintaining high levels of weld quality. The use of controlled carbon levels and improved core constituents for deoxidation and arc stability has resulted in metal cored wires that generate less than half the fume found in standard flux cored consumables. On the contrary, the elimination of shielding gas as advantage of self-shielded wires is disadvantage related to emission of weld fumes containing very harmful compounds.
– Although metal cored wires and self-shielded wires are more expensive (20–25%) than their flux-cored and solid wire counterparts, working with them allows stable arc, good penetration, little spattering. Bearing in mind that the cost of wire represents 10–15% of total welding costs, it pays to invest in more expensive filler material in order to obtain better welded joint.
– Concentrations of emitted SO_2 and CO_2 for both wires are below of exposure limits. Some higher concentration of CO_2 for self-shielded wire is probably due to the increased presence of carbonate and cellulose in flux, which combustion provides gas protection. Concentrations of total dust for both wire are approximately the same, but twice higher than maximum permissible concentrations.
– Concentration of emitted CO for metal cored wire is 10 times higher than for self-shielded wire and 3 times higher than maximum permissible concentrations. Such high concentration of CO is probably consequence of the incomplete combustion of flux, as well as decomposition of CO_2 as the shielding gas component. Bearing in mind the toxicity of CO and the fact that welding does not normally generate CO at high enough levels to be a concern, improving ventilation and wearing respiratory protection (air respirators or self-contained breathing apparatus) must be obligatory.
– Special attention must be paid to the high concentration of manganese in metal cored wire, as well as high concentrations of phosphorus and aluminum in self-shielded wire. Good industrial hygiene practices recommend that engineering controls be used to reduce environmental concentrations to the permissible exposure level. Therefore, local exhaust ventilation or respiratory protective devices and dust suppression with water, must be carried out.
– Conducted experimental measurements of emission of certain elements did not show higher toxicity of self-shielded wire compare to metal cored wire. Definitely, further research should be focus on more detailed analysis of other toxic elements that are assumed to exist in both flux wire. With a new level of understanding of improved processes and health risks, the entire welding industry will benefit and progress.

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